A STUDY OF THE SEISMIC WAVES SKS AND SKKS*

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ABSTRACT

Arrival times, amplitudes, and periods of the seismic phases SKS and SKKS have been investigated for shallow, intermediate, and deep earthquakes recorded at Pasadena and Huancayo, Peru. New observed time-distance curves are constructed for depths of <60, 100, 200, and 600 kilometers. Travel times for the core have been calculated from shallow-shock time data. Slight modification of wave velocity just inside the core and of travel times within the core are suggested. Calculated travel times of SKS, SKKS, and SKKKS are in good agreement with observations.

Energy parameters determined from observed amplitude/period ratios are found in only fair agreement with those calculated from theory. Observed energies are too large for most of the phase components and depths considered. The horizontal components of SKKS over the whole distance range, and of SKS at $\Delta \leqq 100°$ for all depths, yield observed energies less than those predicted by theory. Both discrepancies are at least qualitatively explained by a proposed nonspherical distribution of shear strain about the fault source, and by abnormal absorption in the outer 700 kilometers of the core. Anomalous observed energies, as functions of epicentral location, are also accounted for by the proposed nonspherical distribution of energy.

Introduction

An investigation of wave arrival times, amplitudes, and periods for the seismic phases SKS and SKKS has been made on more than 1,200 seismograms of shallow, intermediate, and deep earthquakes recorded at Pasadena, California or Huancayo, Peru. Epicentral distances for these shocks are between 75° and 175° from the two stations. Selected well-recorded shocks in this same distance range have been utilized in first-motion and polarization studies.

Seismograms at Pasadena found most useful in this study are those recorded by Benioff long-period vertical and horizontal component electromagnetic instruments (pendulum period 1 second, galvanometer period 90 seconds), and by Wood-Anderson torsion instruments (period 6 seconds). Huancayo records used are from Wenner horizontal seismographs with response characteristics very similar to those of long-period Benioff instruments. Eighty-five per cent of all amplitude and period readings were made on records of instruments the magnifications of which are fairly accurately known. The remaining measurements are used only in travel-time studies.

Data from vertical-component instruments are fewer and cover a more restricted range of distance. This results from the fact that no suitable long-period vertical instrument is available at Huancayo, and that records from torsion instruments were available at Pasadena before those from long-period vertical instruments with known magnification. Short-period Benioff electromagnetic instruments have magnifications too low for wave periods characteristic of the SKS group to find extended use.

Travel Times

Observed travel times.—Because of the considerable effect of the slope of time-distance curves upon calculations of expected energy for a particular phase, a complete

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TABLE 1

SHALLOW EARTHQUAKES
(Times for surface focus in min:sec.)

Dist.	SKS	SKKS	SKKKS	Dist.	SKS	SKKS	SKKKS
deg.				deg.			
76	(22:00)	....	....	130	26:27	28:15	28:43
78	(14)	....	....	132	31	27	57
				134	36	38	29:10
80	(27)	....	....	136	40	49	23
82	(41)	....	....	138	44	29:00	36
84	54	....	....				
86	23:06	23:25	....	140	47	11	49
88	19	39	....	142	50	22	30:05
				144	53	34	18
90	31	54	....	146	56	45	31
92	42	24:08	....	148	58	56	44
94	54	22	....				
96	24:04	37	....	150	27:00	30:07	57
98	14	51	(24:53)	152	02	18	31:09
				154	04	29	22
100	25	25:06	(25:08)	156	06	40	34
102	34	20	(23)	158	07	51	47
104	43	34	37				
106	53	47	52	160	08	31:01	59
108	25:02	26:01	26:07	162	09	12	32:12
				164	10	23	24
110	11	14	21	166	11	34	36
112	20	27	35	168	12	44	48
114	28	40	50				
116	36	52	27:04	170	13	54	33:01
118	44	27:03	18	172	14	32:04	....
				174	14	14	....
120	52	17	33	176	15	....	....
122	26:00	29	47	178	15	....	....
124	07	40	28:01				
126	14	52	15	180	16	....	....
128	21	28:04	29				

restudy and determination of the travel times of the SKS group has been carried out. Tables 1 and 2 contain observed travel times for the phases and depths studied. "Shallow" depth is here considered to include shocks down to 60 kilometers below the surface. To simplify comparison with other published travel times, the observed times for shallow earthquakes have been corrected to a hypothetical surface focus. Observed times for intermediate and deep earthquakes have been corrected to the nearest 100 kilometer level shown.

Comparison of these times with those previously determined is hampered by the fact that few tabulations by other workers are completely observational, particularly for other than shallow foci. Residuals in seconds between published times of Gutenberg and Richter (1939, pp. 118–129)[1] and those of the author for SKS and

[1] For references see list at the end of this paper.

SKKS of shallow shocks are as follows (plus values indicate earlier times for the new data):

	80°	90°	100°	110°	120°	130°	140°	150°	160°
SKS	0	0	+1	+1	+2	−7	− 4	−3	....
SKKS	....	....	+6	+1	+1	+5	+12	+17	+21

Agreement for SKS is in general good. The larger residuals between 130° and 140° are near the intersection of the theoretically expected branches of this phase. While this intersection of the two principal branches is reflected in a rather sharp slope change of the new curve, observation of the later segments of these branches has not been made.

TABLE 2

INTERMEDIATE AND DEEP EARTHQUAKES

(Travel times in min:sec. for depths in kilometers shown at head of appropriate column)

Dist. (deg.)	SKS			SKKS		
	100	200	600	100	200	600
80	22:22	21:52	20:46	....	....	....
85	49	22:22	21:16	....	....	....
90	23:15	51	43	23:27	23:00	21:52
95	41	23:19	22:08	58	34	22:24
100	24:06	45	32	24:28	24:06	54
105	30	24:09	55	58	37	23:23
110	52	32	23:17	25:28	25:07	53
115	25:14	52	37	58	36	24:22
120	33	25:12	54	26:28	26:05	52
125	50	31	24:09	57	33	25:20
130	26:04	48	....	27:25	27:00	(49)
135	17	....	....	53	....	....
140	27	....	....	28:19	....	....

Observations of SKS at epicentral distances less than that of its point of intersection with the S curve at 83° are few. Of 25 station-shocks studied in the distance range 75°–83°, only eight identifications of SKS following S could confidently be made.

It is felt that observed times for SKS are now within the limits of error set by the determination of epicenters and origin times, and by variable crustal effects. Additional time-distance data for SKKS and SKKKS would be of value.

Core travel times.—Travel times between points on the surface of the core have been calculated by the method of Wadati and Masuda (1934), using SKS − ScS and (SKKS − ScS)/2. Observed travel times from Table 1 were combined with data for ScS given by Gutenberg and Richter (1939, p. 106). Data from SKS yield times from about 23° to 180° in the core, but at distances greater than 120° a different branch is involved. SKKS supplies travel times for core distances of 13° to 74°. Results from the two sets of data agree very well, being usually within 3 seconds at common distances. Table 3 contains averaged core travel times from these two sources. Columns two and three contain times from Gutenberg (1951) and Jeffreys (1939), respectively, for comparison. Times for the beginning of Jeffreys' second branch (cusp at 88°) are not shown. It is to be noted that the new times are generally in good agreement with previously published data except at short distances, where a steeper curve slope, and hence lower velocity, is here required.

TABLE 3

CALCULATED TRAVEL TIMES BETWEEN POINTS ON THE SURFACE OF THE CORE
(Nelson, N; Gutenberg, G; Jeffreys, J)

Δ_K	t_K(N)	t_K(G)	t_K(J)	Δ_K	t_K(N)	t_K(G)	t_K(J)
5	0:40	0:37	0:37	125	....	10:55	....
10	1:19	1:15	1:15	130	....	11:06	....
15	57	52	52	125	....	10:55	....
20	2:34	2:29	2:28	120	....	44	....
25	3:10	3:06	3:04	115	....	33	
30	44	42	39	110	....	22	....
35	4:18	4:17	4:13	105	....	13	....
40	48	51	46	100	....	03	....
45	5:19	5:23	5:18	105	....	13	10:10
50	48	53	48	110	....	22	19
55	6:16	6:21	6:17	115	....	30	28
60	42	47	45	120	10:40	39	38
65	7:07	7:11	7:11	125	50	47	46
70	32	34	36	130	59	55	55
75	55	56	8:00	135	11:07	11:03	11:03
80	8:18	8:19	22	140	14	10	10
85	39	40	43	145	20	16	16
90	9:01	9:01	9:03	150	25	22	22
95	21	21	22	155	29	27	27
100	40	40	40	160	32	32	31
105	59	59	56	165	34	35	34
110	10:15	10:14	10:11	170	36	37	36
115	28	28	24	175	38	39	38
120	42	42	37	180	39	40	38

Calculated times of the SKS group.—Using combined time-distance values of the core from table 3 and the ScS data noted above, travel times of SKS, SKKS, and SKKKS for surface foci have been calculated. The times here proposed for the core have been used up to 120°. For the branches, the times of Gutenberg were used because his data seem in better agreement with core times here determined near this distance range. From 120° outward on the third branch, the Gutenberg and Jeffreys times, which agree within one second, were favored.

The resulting travel times are shown in the second columns of tables 4 and 5. The first column contains observed times from table 1 for ease of comparison. The

TABLE 4

CALCULATED TRAVEL TIMES FOR SKS FOR SURFACE FOCUS, IN MIN:SEC.
(For last two columns see text)

Dist.	t observ. (N)	t calc. (N)	Residuals (G and R)	Residuals (J)
deg.				
80	(22:27)	22:22	−1	−2
85	23:00	23:01	0	0
90	31	31	−1	−2
95	59	59	−1	−2
100	24:24	24:24	−2	−3
105	48	48	−3	−3
110	25:11	25:10	−4	−2
115	31	31	−4	−1
120	52	52	−2	+2
125	26:11	26:10	−1	+4
130	26	25	−2	+5
135	....	39	−3	....
140	....	50	−5	....
130	....	26:28	(−6)	....
125	....	17	....	....
120	....	07	(−5)	....
115	....	25:58	....	....
110	....	48	(−3)	....
115	....	58	−3	+4
120	....	26:07	−3	+3
125	....	16	−4	+3
130	26	25	−4	+3
135	32	34	−4	+3
140	47	42	−5	+3
145	54	50	−5	+3
150	27:00	56	−7	+2
155	05	27:02	....	+2
160	08	06	−9	+1
165	11	09	....	0
170	13	12	....	0
175	14	14	....	+1
180	15	15	−5	+1

third and fourth columns show residuals from published data by Gutenberg and Richter (1939) and Jeffreys (1939), respectively. A similar designation by initials is used. Residuals are taken with respect to times in column 2; therefore positive residuals indicate earlier times for the published data than those here calculated, and negative residuals later times.

Amplitudes and Energy

Comparison of observed and calculated energy.—Recent studies by many workers have emphasized the importance of wave energy considerations in evaluating common assumptions regarding our hypothetical earth model. Comparison of observed energies and those calculated from elastic-wave theory requires the use of a parameter which can be determined both from seismograms and from theoretical gound displacements. Gutenberg (1945*a*, 1951) has set up such a parameter, A, which may be defined for the observational case (A_o) as

TABLE 5

Calculated Travel Times for SKKS and SKKKS for Surface Focus, in Min:Sec.

Dist.	SKKS				SKKKS		
	t obs. (N)	t calc. (N)	Residuals (G & R)	Residuals (J)	t obs. (N)	t calc. (N)	Residuals (J)
deg.							
80	....	22:33	....	...	....	22:34	....
85	....	23:12	...	+7	....	23:14	....
90	23:54	49	...	+7	....	52	+9
95	24:29	24:25	−4	+7	....	24:30	+10
100	25:06	25:02	−1	+8	25:08	25:08	+11
105	41	37	+1	+7	45	46	+13
110	26:14	26:10	+2	+5	26:21	26:22	+12
115	46	44	+4	+4	57	58	+12
120	27:17	27:16	+4	+2	27:33	27:34	+12
125	46	48	+5	+1	28:08	28:10	+12
130	28:15	28:19	+5	−1	43	46	+12
135	44	49	+4	−2	29:18	29:21	+12
140	29:11	29:18	+3	−3	52	55	+11
145	40	46	+2	−4	30:25	30:28	+9
150	30:07	30:14	+2	−4	57	31:01	+8
155	34	40	+1	−6	31:28	33	+6
160	31:01	31:06	+1	−6	59	32:05	+5
165	29	31	0	−7	32:30	36	+3
170	55	56	−1	−7	33:01	33:07	+1
175	32:19	32:19	...	−8	....	37	−1
180	43	42	−4	−8	....	34:06	−3

$$A_0 = M - \log \frac{u, w}{T} - G(M - 7); \tag{1}$$

and for the theoretical case for core phases (A_t) as

$$A_t = C - \log Q_H,\ Q_Z - 0.5 \log F + 0.217\, kD - \log \frac{\tan i_0}{\sin \Delta} \cdot \frac{di_0}{d\Delta}. \tag{2}$$

Equation (2) is a convenient form of the equation for ground displacement due to seismic waves given by Zoeppritz (Zoeppritz, Geiger, and Gutenberg, 1912). In these equations, M is the magnitude of the shock (Richter, 1935; Gutenberg, 1945*a*, *b*); u and w, the horizontal and vertical ground displacements, respectively (u is the vector sum of two perpendicular horizontal displacements); T is the period of the wave; Q is the ratio of ground displacement to incident amplitude; F is the product of ratios of refracted or reflected energy to that incident at each discontinuity en-

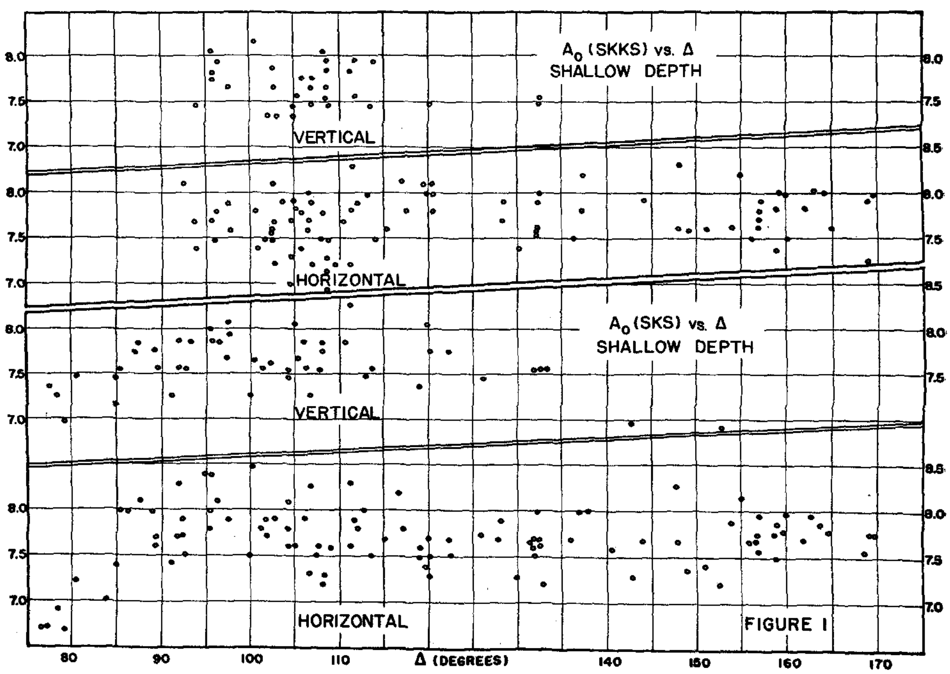
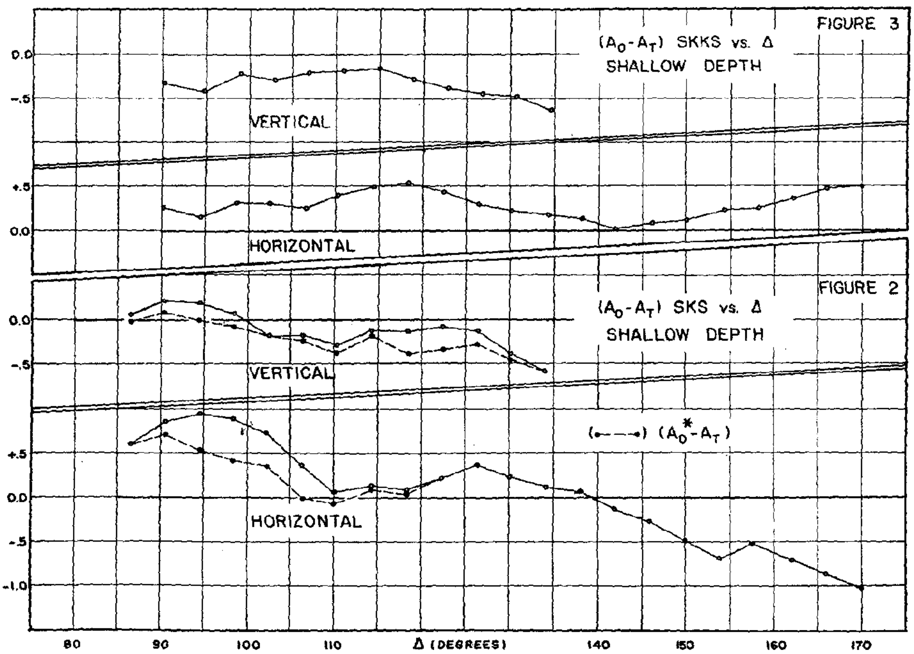


Fig. 1.

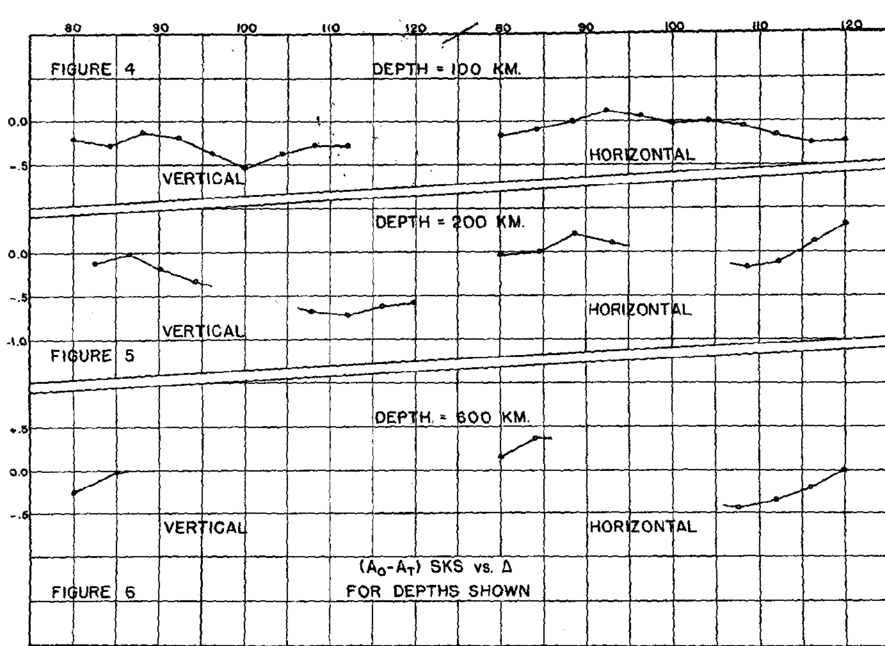
countered; D is the path length, and k the absorption coefficient per unit path length; i_0 is the angle of incidence of a ray at the surface (here assumed equal to the angle of incidence at the source for core waves); Δ, the angular distance in degrees; and G and C, empirical constants. For discussion and evaluation of these quantities see Gutenberg (1944, 1945*a*, 1951).

Ground amplitude/period ratios have been determined from seismograms for which instrumental magnifications are known. Figure 1 is a plot of A_u and A_w (horizontal and vertical components of A_o) as a function of epicentral distance for SKS and SKKS from shallow earthquakes. A_o for SKS in intermediate and deep shocks has also been calculated from (1) for a restricted distance range, but is not shown graphically here.

Values of A_t have been calculated from (2) for SKS and SKKS from shallow shocks, and for SKS from foci at depths of 100, 200, and 600 kilometers. Comparison of these parameters is affected by forming the residual $(A_o - A_t)$. Because of the logarithmic forms of these quantities, the residual is actually the logarithm of a ratio between the observed and the theoretically expected energies. Figures 2



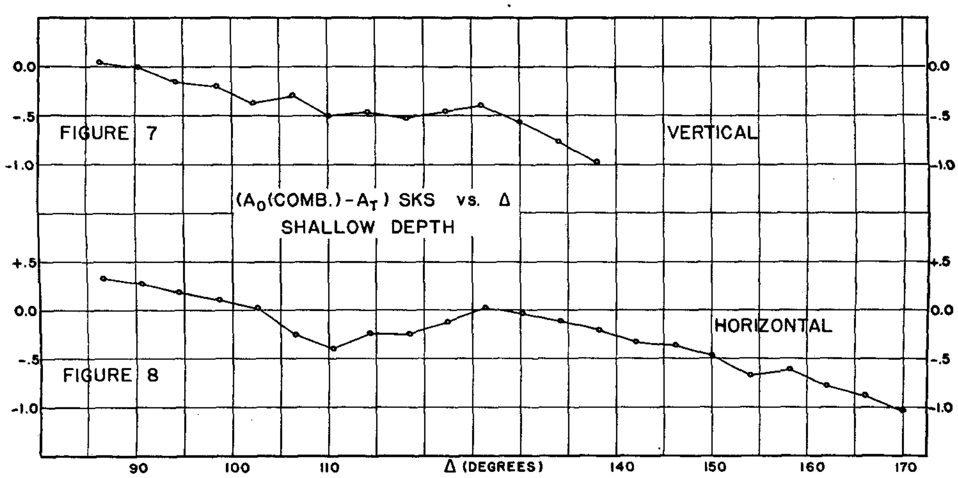
Figs. 2 and 3.



Figs. 4–6.

through 6 show this ratio, for both horizontal and vertical components, plotted as logarithms as a function of epicentral distance. A positive residual indicates that the observed energy is less than that predicted by theory, and conversely for negative residuals. Because of errors and uncertainties in calculating both A_o and A_t, residuals not exceeding 0.25 are considered to indicate agreement of theory with observation. This represents a factor of 1.8 (antilog of 0.25) between observed and theoretical values.

All observations are in only fair agreement with theory. SKS residuals for shallow shocks seem particularly irregular. Because SKS in shallow earthquakes clearly



Figs. 7 and 8.

exhibits the phenomenon of multiplicity, the effect on the residuals of the energy contained in these multiple phases was investigated. In shallow earthquakes the later SKS phases frequently have larger amplitude/period ratios than the principal phase. The dashed lines in figure 2 give the energy residuals using A_o for the strongest phase in the SKS group ($A_o{}^*$) on each seismogram. A slight improvement is noted.

A much greater improvement obtains when the energy in all SKS phases on one seismogram is summed in the A_o term. Figures 7 and 8 are plots of the new SKS residuals. Anomalies in these latter two figures demand an entirely different causal hypothesis over that which might be deduced from figure 2. The same procedure was not extended to the other phases and depths studied, because phase multiplicity is much less pronounced in those instances.

The principal discrepancies between observed energies and those calculated from theory may be summed up from figures 3 through 8 as follows:

A. A_u for SKS from shallow shocks is smaller than expected for $\Delta < 100°$, and larger than expected at greater distances.

B. A_u for SKS in intermediate and deep shocks also changes from too small to too large near $\Delta = 100°$, but are in much closer accord with theory over similar ranges of distance.

C. A_u for SKKS from shallow shocks is smaller than expected over the whole distance range to 180°; and

D. A_w for both SKS and SKKS is too large at all distances and focal depths, although A_w for SKKS is closest to that predicted by theory.

Having eliminated effects on A_o of energy contained in the multiple phases, the remaining energy discrepancies must be explained in terms of variations in A_t. This of course necessitates departure from the simplified theory which is the basis for equation (2). All quantities in this equation which appreciably affect A_t have been examined to see if their variation could resolve the remaining energy residuals. Physically acceptable variations in wave velocities near the surface and the core boundary, in slope of the travel-time curves, and in refraction losses all lead to only second-decimal-place improvements. It is believed that the only two terms in equation (2) which can quantitatively account for the anomalous energies are the constants k and C.

The constant C was originally evaluated by Gutenberg (1945*a*) from the phases P, PP, and S. From its derivation it can depend only on fractions of the given energy going into the fundamental types of waves. Gutenberg found $C = 6.3$, within the limits of accuracy desired, for all wave types. Several assumptions were made in its evaluation, but none with reference to ray path except for the requirement of spherical symmetry of energy propagation about the hypocenter. As pointed out by Nakano (1923), Byerly (1938), and others, this assumption, though convenient, is realistically untenable. Investigation utilizing an alternate energy distribution has disclosed that the constant C should have a lower value for transverse core phases than for transverse mantle phases.

The actual distribution of shear stress near a linear earthquake source is not known, but that suggested in figure 9, *a* fulfills the requirement that shear be a maximum perpendicular to a fault and zero along it. Dashed lines indicate vibration 180° out of phase with that of the solid lines. Figure 9, *b* is the type of rosette which gives the corresponding compressional stress distribution. In evaluating properties of these proposed distributions, it is necessary to consider the actual faulting involved. Thus figure 9, *a* can be thought of as a two-dimensional figure for strike-slip motion on a vertical fault plane. In three dimensions the figure is rotated about the axis of zero shear and becomes a toroid of revolution.

The permutations of many directions of motion on fault planes with various angles of inclination are too numerous for discussion. Instead, a simplification is made by assuming two predominant dip angles and one predominant direction of displacement. The basis for the choice involved is found in recent studies by Benioff which deal with many of the major fault systems of the world (Benioff, 1949; and personal communications). He has found from a detailed study of the seismicity of several of the circum-Pacific arc structures that the hypocenters of shallow, intermediate, and deep shocks, where associated, fall on two surfaces which dip at angles near 30° and 60°, respectively. Transition between the two planes apparently takes place between 175 and 400 kilometers in depth in areas having continental-type rocks on one side of the fault. Where this condition is not met, only the steeper angle is determined. The hypothesis deduced by Benioff to explain the origin of these great fault zones requires predominantly dip-slip displacement.

Figures 10, *a* and 10, *b* illustrate these two conditions in vertical sections through the hypocenter. Angles of departure at the source for all transverse phases with partial core paths are always between 0° and 15°. We may represent this relation in the figures by a cone of incidence with central angle of 30°, axis vertical, and apex at the focus. Study of the figures discloses that the chief characteristics of this energy distribution for dipping faults are: (1) considerable variation in energy with azi-

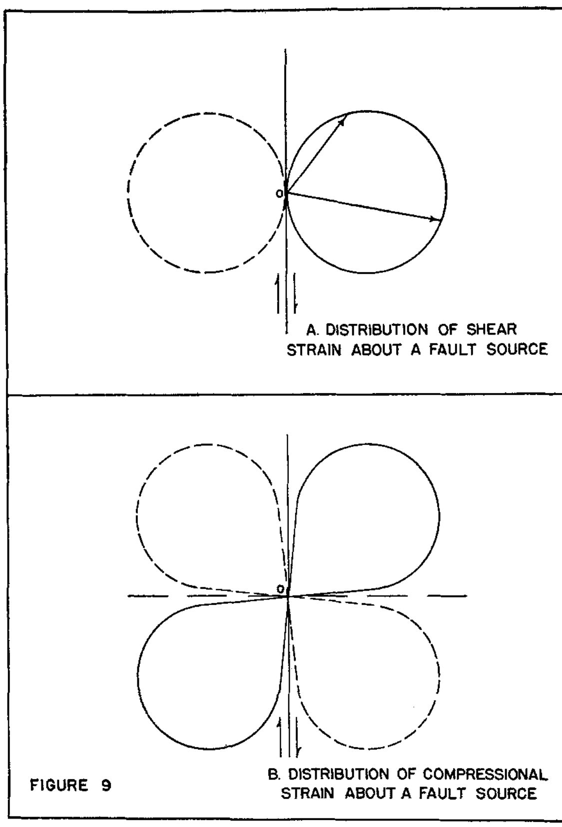


Fig. 9.

muth from the focus, at equal angles of incidence, is possible; (2) there is a variation of energy with varying angle of departure of the rays; and (3) both these variations are increased, although absolute values are decreased, by increased angles of dip of the fault plane (and hence increased depth of focus under the assumptions noted above.)

A similar development is possible for the distribution of dilatational energy. The three-dimensional figure in this instance consists of two mutually perpendicular, intersecting toroids each similar to that for shear. The zones of zero energy are thus greatly reduced and the cone of incidence cuts out surfaces yielding much less extreme variations at all angles of departure and fault-plane attitudes. In other words, the energy-distribution solid is a much better approximation to a sphere.

Figure 10 further indicates that if the rays can have angles of departure at the source of from 15° up to 90° (true for the S phase), and all possible azimuths from the source, average amplitudes observed at a wide net of stations will be *lower* than those which would be determined from SKS or SKKS alone. The difference is obviously greater for shallow shocks (gently dipping plane) than for deeper foci (steeply dipping plane). The lowering of averaged amplitudes is due to a greater effect of the zones of small shear energy at larger angles of incidence, yielding a

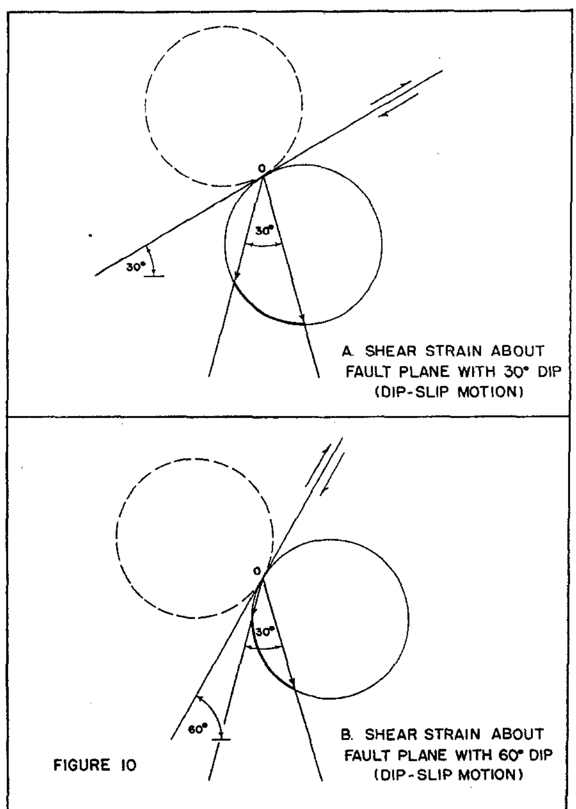


Fig. 10.

higher value of C. If C is too large for transverse core phases, A_t in (2) is too large and the residuals $(A_o - A_t)$ are too small.

In the light of this conclusion we might expect negative residuals for both SKS and SKKS over the whole range of epicentral distance studied. Figures 3 through 8 show this to be the case for SKS only at $\Delta < 100°$, and not the case for the horizontal component of SKKS at any epicentral distance. Thus only the second halves of discrepancies A and B noted above are removed by the assumed energy distribution. Figure 10 can, however, explain the better agreement of deeper shock data with calculated values.

The remaining parts of discrepancies A, B, and C are at least qualitatively resolved by a consideration of the absorption coefficient k. SKS for all depths has positive residuals, hence deficient energy, at epicentral distances less than 100°. Assuming for a moment that this is due to increased absorption in the outer regions of the core, what interrelation with residuals of SKKS would be expected? An SKS ray emerging at 100° has 70° of this path in the core. Thus the equivalent SKKS ray emerges at 170°. If observed energies of SKS are too small at $\Delta < 100°$ because of the abnormal absorption assumed, energies in SKKS, because of its doubled core path, should exhibit roughly twice this discrepancy over the whole range to 170°. Figure 3 shows this to be approximately the case. The validity of this interpretation is further strengthened by an observed phase-period increase with epicentral dis-

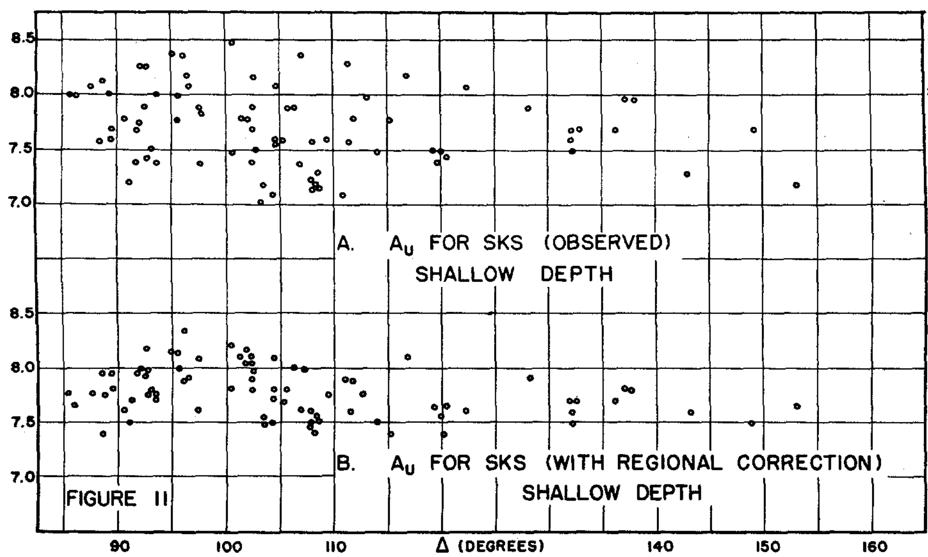


Fig. 11.

tance believed due to selective absorption—a relation which cannot be further discussed here.

A thickness of 700 kilometers for the highly absorptive zone has been determined by calculating the deepest point on a ray having a central angle of 70° in the core by the method of Herglotz and Wiechert. Calculations of probable values of k in the outer core are not possible until adjusted values of C have been determined and the required variation in A_t defined.

No hypothesis for the explanation of discrepancy D above (abnormally large vertical amplitudes) is suggested by either the shear-stress distribution diagrams or the zone of abnormal absorption. Similar findings were obtained by Ergin (1953) for the supposedly minor vertical components of PcS and ScS. Explanation of this phenomenon as a result of refraction to longitudinal vibration at a very near surface discontinuity is not borne out by studies of directions of the first SKS motion. Investigation of polarization of SKS waves has also disclosed appreciable components of SH vibration in the theoretically pure SV motion. The problem of mixed vibration is complex, yet basic, and is worthy of additional data and study.

Anomalous observed energy as a function of epicentral location.—Observed amplitudes and periods of SKS, in themselves, supply another energy relation of interest.

The scatter of A_o values in figure 1 seems in excess of that expected from errors involved. This scatter was analyzed by taking residuals for each determination with respect to a mean curve. A_u for SKS was selected for preliminary study because of a greater number of observations involved. Figure 11, *a* is a plot of A_u from 80 shallow earthquakes particularly well recorded at Pasadena.

Residuals of each observation were analyzed with respect to shock magnitude,

TABLE 6

Regional Correction Factors for Amplitude/Period Ratios Measured at Pasadena

Region	Correction	Region	Correction
Normal depth			
Northern Iran and Turkey	+0.4	Aroe I.	+0.25
North Africa	+0.2	Celebes	−0.2
Southern Antilles and Tierra del Fuego	+0.15	Sumatra	0.0
New Zealand	−0.3	Philippines	+0.2
New Hebrides	+0.2	Formosa and Japan	−0.35
Santa Cruz I.	−0.25	Szechwan, China	−0.1
Solomon I.	+0.3	Burma	−0.4
New Britain	+0.25	Eastern India	0.0
New Guinea	+0.3	Indian Ocean	+0.3
Depth = 100 kilometers			
South America	+0.3	New Britain	0.0
Kermadec I.	+0.2	New Guinea	+0.1
Tonga I.	−0.3	Sunda Arc	+0.25
New Hebrides	+0.2	Marianas I.	+0.25
Santa Cruz I.	−0.2	Celebes	−0.3
Solomon I.	0.0	Philippines	+0.5
Depth = 200 kilometers			
Kermadec I.	+0.2	Celebes	+0.15
New Hebrides	−0.05	Marianas I.	+0.3
Sunda Arc	−0.1	Hindu Kush	0.0

azimuth, epicentral distance, and epicentral location. No consistent deviation with magnitude was apparent, thereby confirming the value of G in equation (1) and extending its use to shear core phases. Also, no dependence of the residuals on either distance or azimuth alone was discovered. The predominant effect upon the magnitude and sign of any particular residual is found to be the geographic location of the earthquake involved. This result was tested by first considering amplitudes of multiple phases in the SKS group, and then by an analysis of all intermediate and deep shock data.

From tables grouping the residuals as functions of latitude and longitude, average residuals for localized areas were determined. Complexities arise in the delineation of boundaries of adjacent regions. This is particularly true for the island arcs of the southwest Pacific. Maps and descriptive data from Gutenberg and Richter (1949) have been used extensively in this determination. The adopted average residuals are summarized in table 6. These residuals can be used as correction factors in determinations of magnitude from SKS at Pasadena by subtracting them from the logarithm of the amplitude/period ratio in equation (1) solved for M.

To illustrate the effectiveness of the average residuals found, they have been applied to the observed A_u values in figure 11, *a*. The corrected A_u values are plotted in figure 11, *b*. It is noted that the scatter is reduced about 60 per cent by this regional correction.

How much of the disagreement in residuals with depth of focus in a single region is real and an indication of very complex structures in the areas involved is not known. Coincidence of all such anomalies with zones of sharply flexed structural trends in the major and minor arc units of the circum-Pacific belt suggests that they are not wholly due to errors and statistical inconsistencies of the method.

Several causal hypotheses for these energy anomalies have been considered. Anisotropy of the medium, near-surface crustal effects at the source, and surface inequalities of the core boundary are all either refuted by the data or can be shown to be quantitatively incompetent to resolve the residuals. Application of the non-spherical energy distribution described above, however, allows quantitative explanation of the residuals of observed energy over the mean in terms of variations in strike of the major fault systems involved with respect to azimuths from Pasadena.

Mooney (1951, p. 26) has tabulated a slightly different energy residual as a function of epicentral region for the phases pP and P observed at Pasadena. His residuals are based on the quantity $(A_t - A_o)$, and hence have signs opposite to those here determined. It is of interest, however, that with reversed signs for one set of data, all the residuals for regions common to both investigations are of similar sign (Marianas Islands, New Guinea, New Hebrides Islands, and Kermadec Islands). Furthermore, all the residuals based on longitudinal phases are of smaller magnitude, as is predicted by comparison of the energy distribution patterns in figure 9 for dilatational and distortional vibration.

Summary and Conclusions

Newly constructed travel-time curves of SKS, SKKS, and SKKKS are believed to be an improvement over previous observed curves since they are in better agreement with calculated arrival times. Observation of the later branched segments has not been possible, but the new SKS curve reflects rather closely the abrupt slope change near 130° at the theoretical branch intersection. Late arrivals of SKS clearly delineate three multiple phases for normal earthquakes, in addition to the principal phase, and at least one for intermediate and deep shocks. Only one phase has been observed for SKKS. It is thought that observed times of SKS are now within the limits of error set by the determination of epicenters and origin times, and by variable crustal effects. Additional time-distance data for SKKS and SKKKS would be of value.

Travel times between points on the surface of the core have been calculated, using SKS and SKKS times from this study, and are presented in table 3. Times from both calculations are in very good agreement over the common range and require a steeper curve slope, and hence slightly lower velocity, just inside the core than the latest published data of both Gutenberg and Jeffreys. Using an averaged core travel-time curve, and times for the later branches not derivable from SKS from Gutenberg (1951), times were calculated for SKS, SKKS, and SKKKS. Agreement with observed times is best for SKS, but residuals for the other two phases never exceed 7 seconds.

Parameters which are measures of wave energy have been determined from observed amplitudes and calculated from elastic-wave theory. Agreement between observation and theory for all phases is in general only fair or even poor. The observed energies are too large for all phases, components, and distances except for the horizontal component of SKKS over the whole range of distance, and of SKS at epicentral distance less than 100°. These anomalies have led to the consideration of a nonspherical energy distribution about the source. A completely quantitative treatment is not possible at this time, but the proposed variations of energy as a function of ray azimuth and angle of incidence from the source can remove most of the observed discrepancies. Remaining residuals of opposite sign are explained on the basis of a highly absorptive zone within the core from its surface down to an approximate depth of 700 kilometers.

Observed-energy parameters show a definite epicentral location dependence. Residuals from mean values are tabulated for several regions as correction factors which can be used at Pasadena in calculations of magnitude from SKS amplitudes for earthquakes of normal and intermediate depths. These energy variations with azimuth and epicentral distance are also qualitatively explained by the nonspherical energy distribution noted above.

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Detailed data, calculations, and results, as well as additional data on phase periods, multiplicity, and polarization are available in the thesis, on file at the California Institute of Technology, Pasadena.

References

BENIOFF, H.

1949. "Seismic Evidence for the Fault Origin of Oceanic Deeps," *Bull. Geol. Soc. Am.*, 60: 1837–1856.

BYERLY, P.

1938. "The Earthquake of July 6, 1934: Amplitudes and First Motion," *Bull. Seism. Soc. Am.*, 28: 1–13.

ERGIN, K.

1953. "Amplitudes of PcP, PcS, ScS, and ScP in Deep-Focus Earthquakes," *Bull. Seism. Soc. Am.*, 43: 63–83.

GUTENBERG, B.

1944. "Energy Ratio of Reflected and Refracted Seismic Waves," *Bull. Seism. Soc. Am.*, 34: 85–102.

1945*a*. "Amplitudes of P, PP, and S and Magnitude of Shallow Earthquakes," *Bull. Seism. Soc. Am.*, 35: 57–69.

1945*b*. "Magnitude Determination for Deep-Focus Earthquakes," *Bull. Seism. Soc. Am.*, 35: 117–129.

1951. "PKKP, P′P′, and the Earth's Core," *Trans. Am. Geophys. Union*, 32: 373–390.

GUTENBERG, B., and C. F. RICHTER

1939. "On Seismic Waves" (fourth paper), *Gerlands Beitr. z. Geophysik*, 54: 94–136.

1949. *Seismicity of the Earth and Associated Phenomena* (Princeton University Press).

JEFFREYS, H.

1939. "The Times of the Core Waves" (second paper), *Mon. Not. Roy. Astron. Soc., Geophys. Suppl.*, 4: 594–615.

MOONEY, H. M.

1951. "A Study of the Energy Content of the Seismic Waves P and pP," *Bull. Seism. Soc. Am.*, 41: 13–29.

NAKANO, H.

1923. "Notes on the Nature of Forces Which Give Rise to Earthquake Motions," *Seism. Bull. Centr. Meteorol. Observ.*, Japan, 1: 92–120.

RICHTER, C. F.

1935. "An Instrumental Earthquake Magnitude Scale," *Bull. Seism. Soc. Am.*, 25: 1–32.

WADATI, K., and K. MASUDA

1934. "On the Travel Time of Earthquake Waves, Pt. 6," *Geophys. Mag.*, Tokyo, 8: 187–194.

ZOEPPRITZ, K., L. GEIGER, and B. GUTENBERG

1912. "Über Erdbebenwellen. V," *Nachr. K. Ges. d. Wiss. z. Göttingen*, math.-phys. Kl., pp. 121–206.

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